All of these benefits of the SDMA system accrue from the use of smart antennas and proprietary signal processing technology. The ability to locate, track, spatially demultiplex, and spatially multiplex signals to and from multiple users results in a significant increase in spectral efficiency not currently achievable by any other system. The compatibility of SDMA with current modulation schemes, and its inherent ability to handle increasing demand (modularity) make it ideal for PCS implementation.

5. Status of SDMA

SDMA technology is a blend of phased-array antenna technology which has been used successfully over the last 40 years in many military applications, proprietary signal processing techniques developed over the last 15 years by principals of Spatial Communications, Inc., and state-of-the-art digital signal processing (DSP) hardware to implement these algorithms in real-time. As such, there is little technical risk involved in implementing SDMA. The critical components of the SDMA system include:

1. antenna arrays and RF frontends,
2. proprietary SDMA signal processing algorithms,
3. DSP hardware to implement these algorithms in real-time,
4. interface equipment to existing base stations.

Of these components, only the interface equipment is still under development. Such interfaces will be designed into the prototype system to be tested within the next year. Since the antenna arrays required are collections of simple antennas currently employed, there is no development required. The proprietary SDMA signal processing algorithms have been coded and tested and are currently available. The demonstrations completed to date involve simulating the RF environment and the antenna arrays. Experimentation is continuing in the UHF band at 900 MHz and at 1.9 GHz to demonstrate the ability of SDMA to successfully track and demodulate cochannel emitters in a controlled RF environment. A working demonstration of the full-duplex SDMA system is expected by the end of summer 1992.

5.1 Computer Simulations

In this section, the results of computer simulations indicating the performance of the SDMA system in its ability to increase capacity and quality in PCSs is presented. The computer model of the RF environment used models two of the dominant effects in urban and rural environments. The first is scattering of the RF energy from nearby structures such as buildings, and results in *Rayleigh fading*. This phenomenon can be viewed essentially as a time-varying antenna gain as seen at the base station where the bandwidth of the temporal variation is directly related to the velocity of the transmitter relative the local scatterers measured in wavelengths per second. For pedestrians, this is not expected to be in excess of 100 Hz and will generally be much less. The second effect is specular multipath with significant delays with respect to the underlying signal bandwidth. This phenomenon can be significant in large urban centers with many tall structures, and in certain geographical areas such as Salt Lake City, Utah where mountainous terrain borders metropolitan centers.

In the first simulation, analog FM handsets (at 1920 MHz) are employed, and it is assumed that the RF environment is similar to that representative of an urban or suburban area in which local scattering effects (within a radius of approximately 100λ) dominate. It is further assumed that the base station is not situated in close proximity (within approximately 10λ) to any (electromagnetic) reflecting structures.

FIG. 5-1 illustrates the capability of SDMA to simultaneously track two transmitters in the same channel, and to spatially demultiplex the received signals to estimate the transmitted waveforms individually. The receiving array is composed of a 10-element uniform linear array of elements spaced one half-wavelength apart, *i.e.*, 7.8 cm at 1920 MHz. The two FM transmitters are moving toward each other and actually cross paths, *i.e.*, the DOAs are at one point during the interval the same. A severe Rayleigh fading environment is simulated with a fade rate in excess of 100 Hz. The receiver outputs are processed in blocks of 400 data vectors (0.05 sec of data sampled at 8 KHz). In spite of the fact that the transmitters are less than $2°$ apart at 1.7 sec, approximately 30 m separation 1 km from the base station, the individual signal waveforms are accurately reconstructed as shown in the lower illustration. This figure clearly manifests the efficacy of the SDMA system as such performance has not been achieved previously. The ability to separate cochannel sources in close proximity to one another and to successfully spatially demultiplex the received signals is unique to SDMA.

FIG. 5-2 is a continuation of FIG. 5-1 illustrating the capability to simultaneously track multiple transmitters in the same channel where the trajectories cross. At the midpoint of the estimation interval, the transmitters are at the same DOA. As is easily seen, the SDMA system tracks the DOAs of the transmitters successfully. The ability to track intersecting trajectories of cochannel transmitters from DOA measurements made by an array of sensors is unique to SDMA.

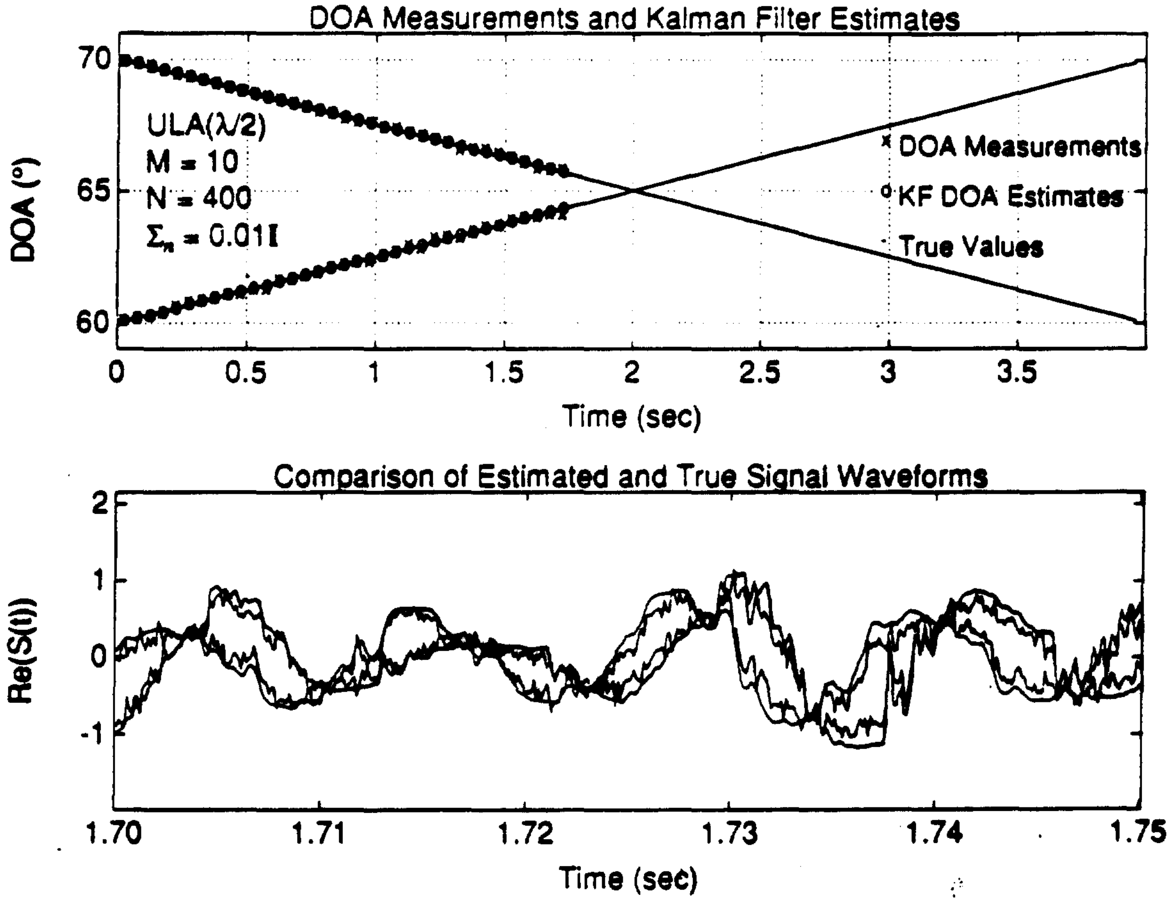

Figure 5-1: Simulated SDMA Processor Outputs — DOA Tracking and Signal Copy of Closely Spaced Moving FM Transmitters in a Severe Rayleigh Fading Environment

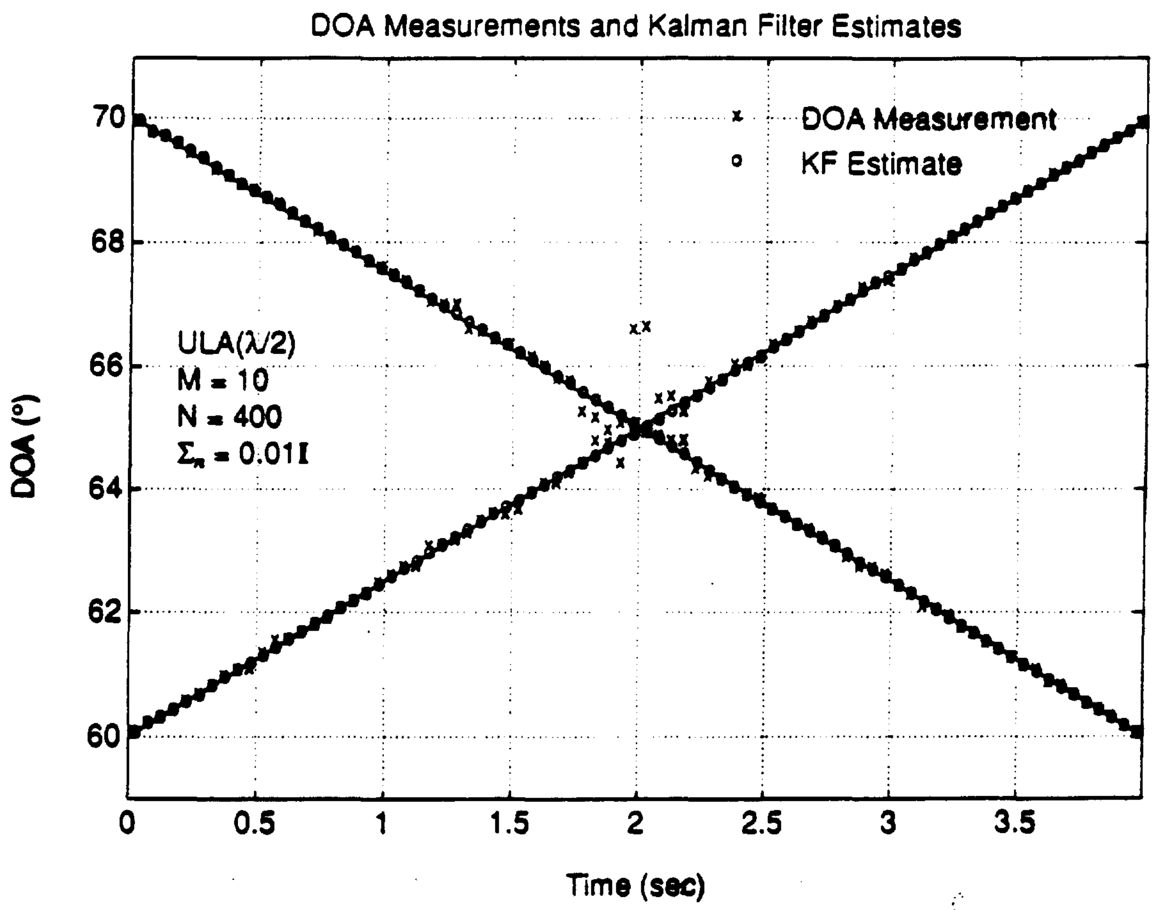

Figure 5-2: Simulated SDMA Tracker Outputs — DOA Estimates and Kalman Filter Tracking of FM Transmitters Crossing Tracks in a Severe Rayleigh Fading Environment

FIG. 5-3 illustrates the compatibility of the SDMA concept with proposed digital technology such as that to be implemented in CT-2, CT-2plus or CT-3. An RF environment similar to that assumed in the first simulation is again used. Here however only $20\,\mu$ *sec* of data are shown so the effects of the Rayleigh fading are not noticeable. Three sources at $20°, 40°$, and $60°$ with respect to the line axis of a 10-element uniform linear array of omnidirectional antenna elements are simulated. The baud-rate rates are arbitrarily chosen to be $1\,MHz, 1\,MHz$, and $500\,KHz$ respectively, and the effective signal-to-noise ratio (SNR) is approximately 0dB. The upper plot shows the output of the first antenna element, and the SNR is clearly seen to be nearly 0dB, *i.e.*, the signal and noise amplitudes are nearly equal. The lower four smaller plots show the three spatially demultiplexed signals and the angle of the output of the first antenna for comparison. They clearly indicate the ability of the SDMA system to not only spatially demultiplex the digital transmissions, but also indicate the performance improvement achievable. There is roughly a factor of 10 improvement in spatial demultiplexer output SNR as is quite evident. The DOA estimates were based on 200 snapshots ($20\,\mu sec$ of data), and not only was the number of signals (3) correctly detected by the SDMA detector, the estimated DOAs were all within $0.5°$ of the true values. The capability to obtain estimates of such quality, and to spatially demultiplex spread-spectrum digital signals in these cochannel interfering environments is unique to SDMA.

FIG. 5-4 illustrates the improvement of the SDMA robust spatial multiplexing scheme over other techniques. In the simulation, three transmitters were located at $40°, 50°$ and $90°$ respectively with respect to the line axis of a 10-element $\lambda/2$-spaced uniform linear array. The estimated directions of arrival based on 1000 data vectors were within $0.05°$ of the true values, and spatial multiplexing weight vectors were computed on the basis thereof. The illustration shows the results of spatial multiplexer design for transmission to the receiver at $90°$; a design objective being the minimization of power in the direction of the receivers at $40°$ and $50°$. The feasibility of the SDMA (robust) spatial multiplexer is clearly manifest.

5.2 Laboratory Test Results

SDMAs ability to increase capacity and quality in PCSs, as demonstrated in preliminary experimental results, is presented in this section. In this section, the results of preliminary experimental data analysis performed indicating the performance of the SDMA system in its ability to increase capacity and quality in PCSs is presented. In the first scenario, signals similar to those emitted by CT-2 handsets were employed. These tests were run in an anechoic chamber so as to provide a clean RF environment for initial

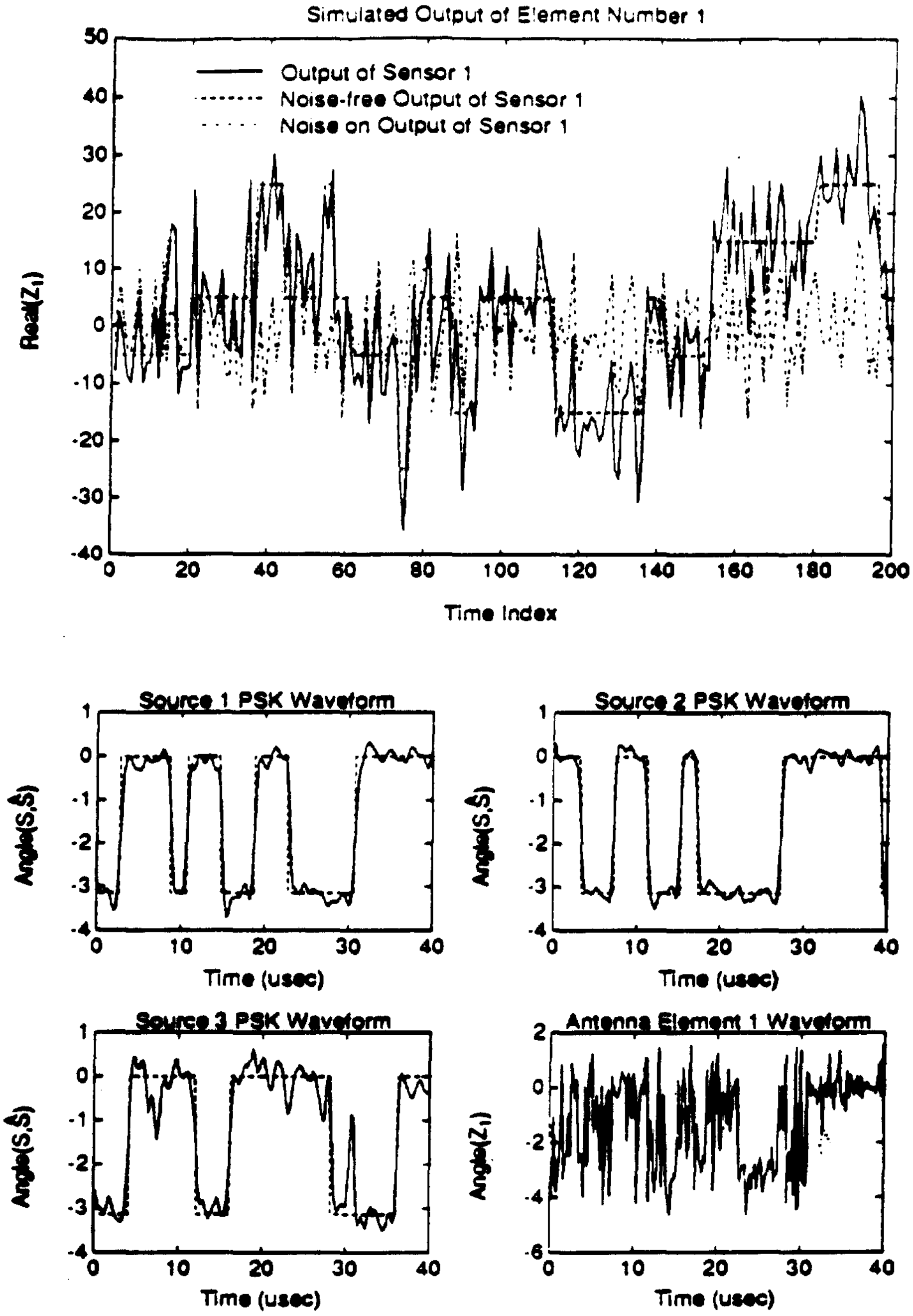

Figure 5-3: Simulated SDMA Signal Copy Outputs — Antenna Measurements and Spatially Demultiplexed Digital Signals in a 0 dB SNR Environment

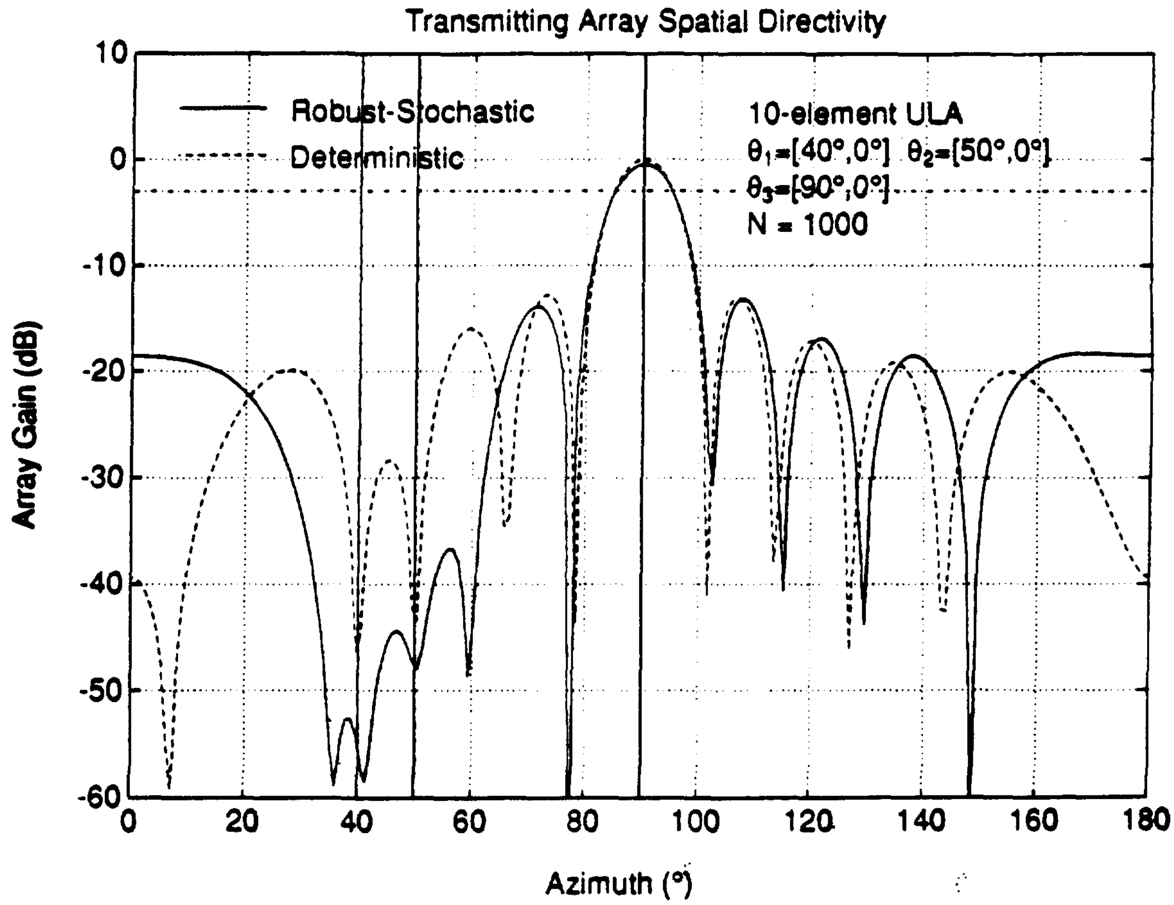

Figure 5-4: SDMA Spatial Multiplexer Directivity

testing and debugging. Further tests in normal and difficult RF environments will be performed as described in the Section 5.3.

The initial test program consisted of construction of a receive array of six (6) vertical dipole elements (approximately 6 cm in length or $\lambda/2$ at 2.5 GHz) mounted 17 cm from a ground plane. RF absorbing material was placed between the elements (which were themselves mounted on PVC pipe with epoxy) and the backplane to minimize reflections and the effects of resonance. The cost of materials for the elements was on the order of $200. The relative locations of the elements are shown in Figure 5-5.

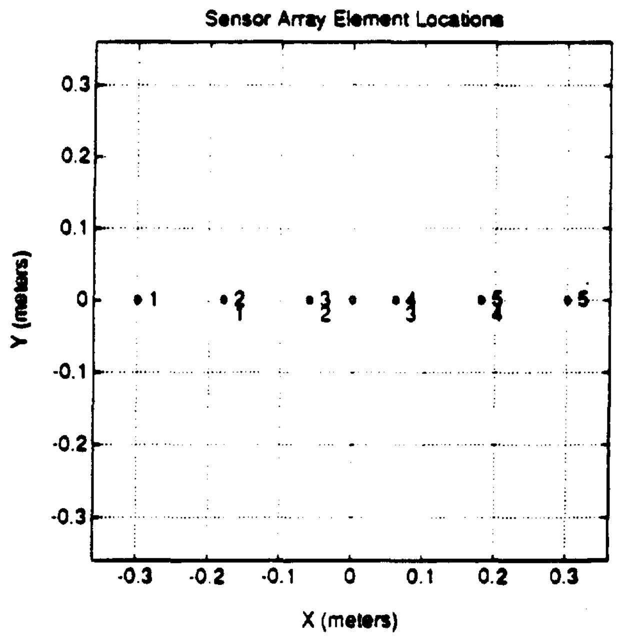

Figure 5-5: Experimental Uniform Linear Array (ULA) Element Relative Locations

5.2.1 Two Sources Closely Spaced

Two vertically polarized sources were used in the first experiment. The center frequency (or RF carrier) was set to 1.200 GHz resulting in half-wavelength ($\lambda/2$) adjacent element spacing. The modulation type was binary frequency-shift-keyed (BFSK) similar to that employed in CT-2 systems. The hop or chip rate was set to 2 KHz for both waveforms. For one of the waveforms, a 2 KHz deviation was used, and for the other, 5 KHz. These chip rates and deviations were chosen so as to minimize any distortion effects resulting from the front-end anti-aliasing and image rejection filters. The multichannel data were sampled at 150 KHz, and up to 8 k samples were taken from each of the 6 antennas.

The signals were set to be roughly 20 dB and 14 dB above the noise, resulting in $+6$ dB and -6 dB carrier-to-interference (C/I) ratios respectively. The sources were at 100° and 110° angles with respect to the axis of the array. The (real part of the) output of sensor 1 is shown in Figure 5-6 along with the (real part of the complex) noise which was added as well.

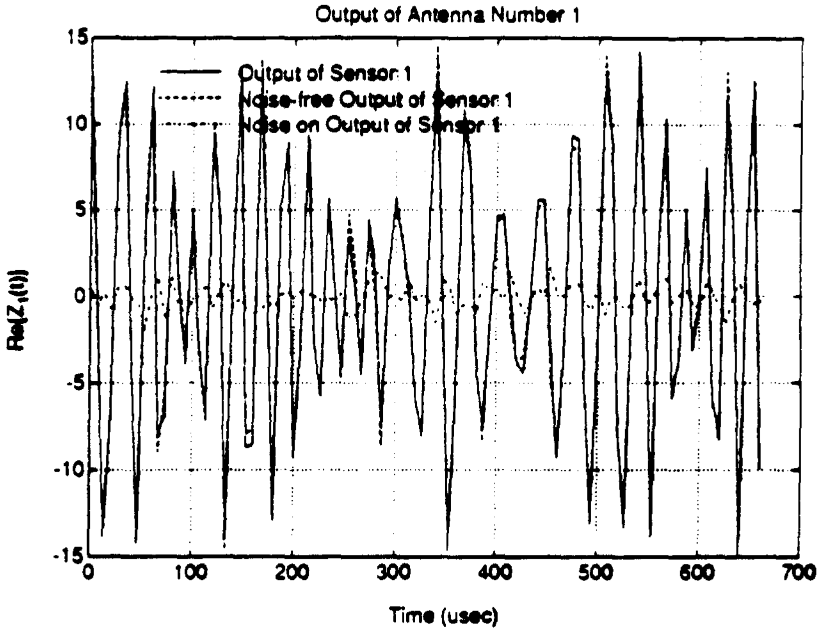

Figure 5-6: Experimental ULA Output of Sensor Number 1 - Case 1

The results of applying Spatial Communications, Inc. proprietary signal processing algorithms are given below. The estimated source DOAs were based upon 4 k snapshots and are given below:

Parameter	Estimate	True Value
$\hat{\theta}_1$	100.5°	100°
$\hat{\theta}_2$	110.1°	110°

The results clearly manifest the ability of SDMA to localize two cochannel sources well within a Rayleigh beamwidth. The results of applying Spatial Communication's proprietary signal estimation algorithms are shown in Figure 5-7 where the true signal, estimated signal, and the residual (or difference) are shown. As indicated in the residuals in Figure 5-7, the post-processing C/I ratios are approximately 30 dB. The signals have been successfully *spatially demultiplexed* and are easily decoded.

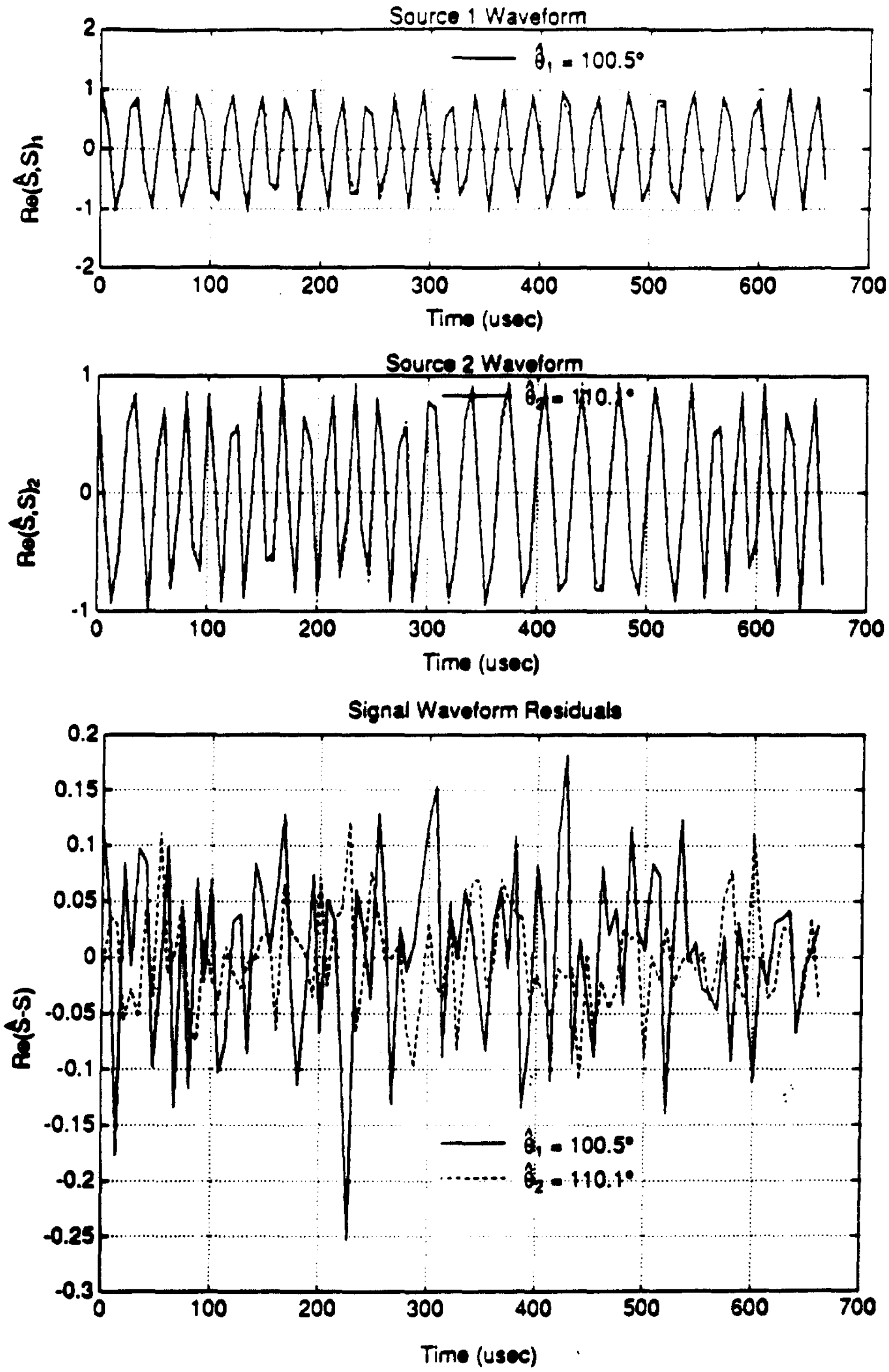

Figure 5-7: Experimental Signal Copy Results - Case 1

5.2.2 Two Source Case with Rayleigh Fading

To investigate the effects of Rayleigh-type fading on the SDMA system performance, a third source was added, coherent with the first and placed 2° away. Thus, for this test there were two coherent sources at 68° and 70° respectively, and a second independent source at 110°. The *multipath* of the first source was attenuated by 3 dB and delayed by a small fraction of a baud, thus representing a nearby scattering center with a scattering coefficient magnitude of 0.5. The output of sensor 1 is shown in Figure 5-8 along with the (real part of the complex) noise which was added as well.

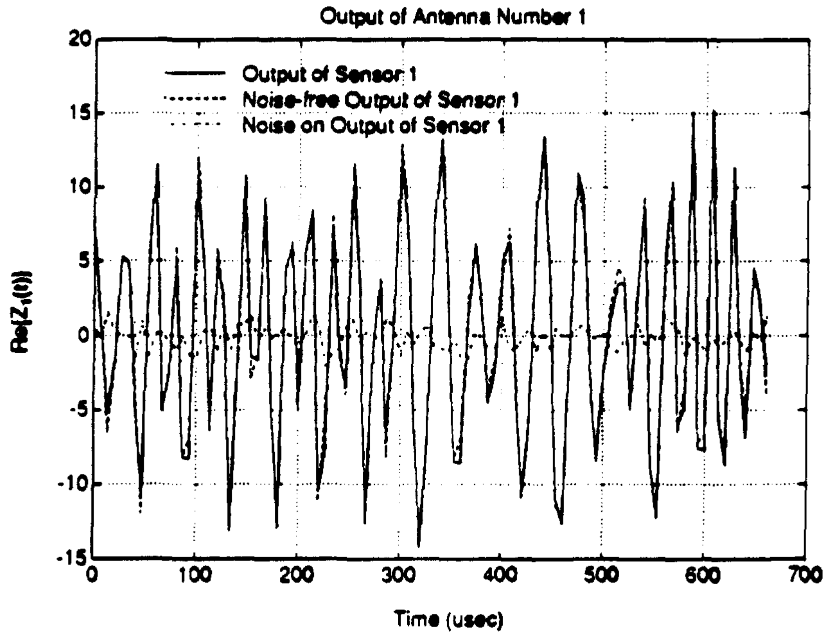

Figure 5-8: Experimental ULA Output of Sensor Number 1 - Case 2

As is the case with Rayleigh fading, the *multipath cluster* appears as a single source and the estimated direction-of-arrival indicates the location of the cluster. The estimated source DOAs were based upon 4 k snapshots and are given below:

Parameter	Estimate	True Value
$\hat{\theta}_1$	80.3°	78°-80°
$\hat{\theta}_2$	110.1°	110°

The results clearly manifest the ability of SDMA to localize two cochannel sources in the presence of this Rayleigh fading (near multipath). The results of applying Spatial Communication's proprietary signal estimation algorithms are shown in Figure 5-9 where the true signal, estimated signal, and the residual are shown. As indicated in the residuals in Figure 5-9, the post-processing C/I ratios are approximately 20 *dB*-30 *dB*. Again, the signals have been successfully spatially demultiplexed and are easily demodulated and decoded.

5.2.3 Three Source Case

To investigate the performance of the SDMA system with three sources, a third independent source was added. For this test, there were sources at 65°, 90°, and 110° with amplitudes 10, 5, and 10 relative to unit power noise respectively. The (real part of the) output of sensor 1 is shown in Figure 5-10 along with the (real part of the complex) noise which was added as well.

As is the case with Rayleigh fading, the *multipath cluster* appears as a single source and the estimated direction-of-arrival indicates the location of the cluster. The estimated source DOAs were based upon 4 *k* snapshots and are given below:

Parameter	Estimate	True Value
$\hat{\theta}_1$	64.6°	65°
$\hat{\theta}_2$	90.1°	90°
$\hat{\theta}_3$	109.7°	110°

These results clearly indicate the ability of SDMA to localize three cochannel sources in close proximity with varying power levels. The results of applying Spatial Communication's proprietary signal estimation algorithms are shown in Figure 5-11 where the true signal, estimated signal, and the residual are shown. As indicated in the residuals in Figure 5-11, the post-processing C/I ratios are approximately 20 *dB*-30 *dB*. Compared to the initial C/I of approximately -6 *dB*, this represents a processing gain of approximately 35 *dB*.

5.3 Future Experimentation

In this section, a two-year experimental test plan is outlined. Beginning with preliminary field tests that are already underway, the plan culminates in final system certification leading to mass production and installation of SDMA technology base stations in fully operational PCNs. The plan is summarized in Figure 5-12.

5.3.1 Preliminary Field Trials

Through July of 1992, the experiments currently being conducted in a controlled RF environment (anechoic chamber) will continue. These tests are being conducted to ascertain the performance envelop of the SDMA receive system in progressively challenging

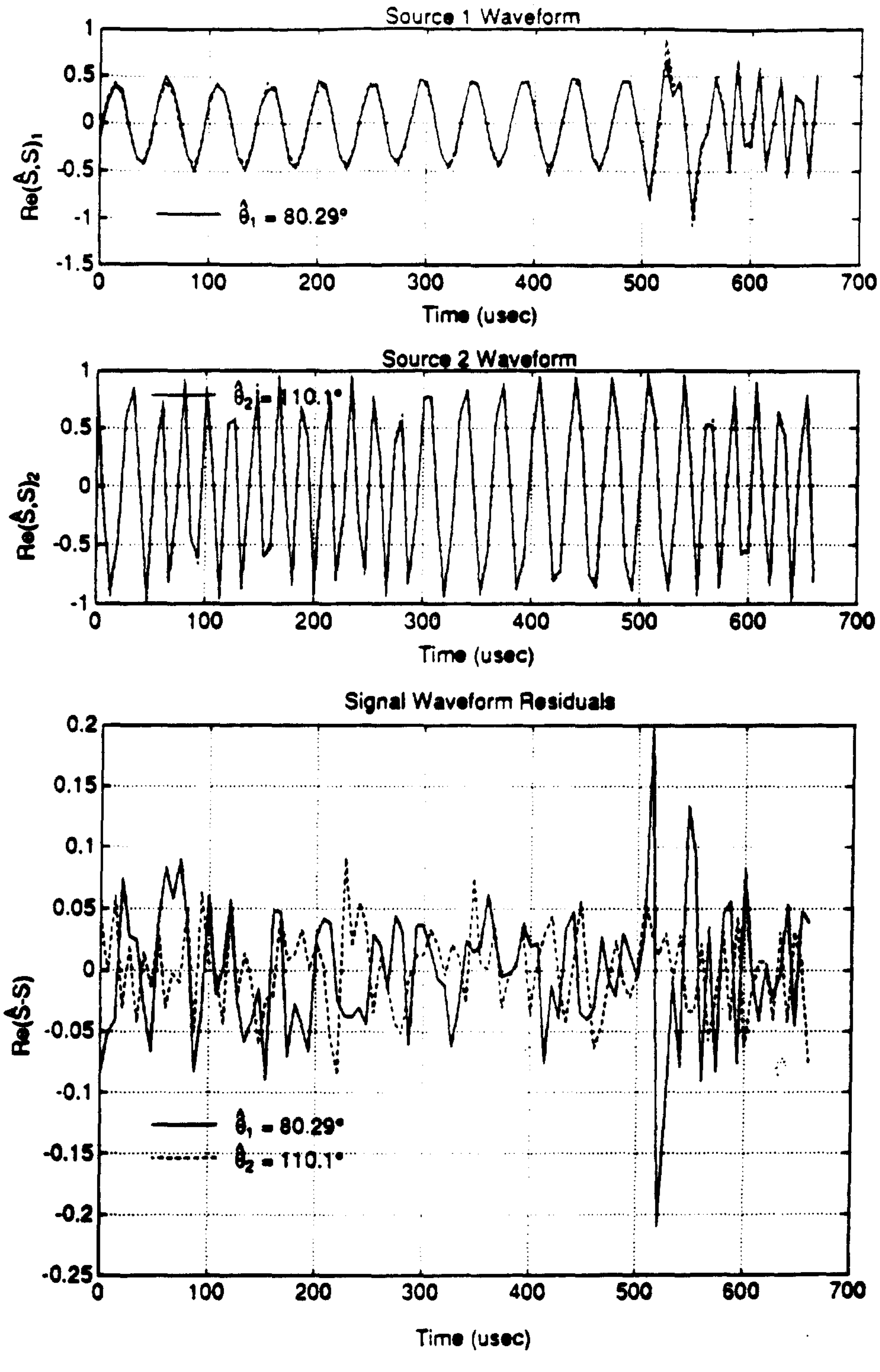

Figure 5-9: Experimental Signal Copy Results - Case 2

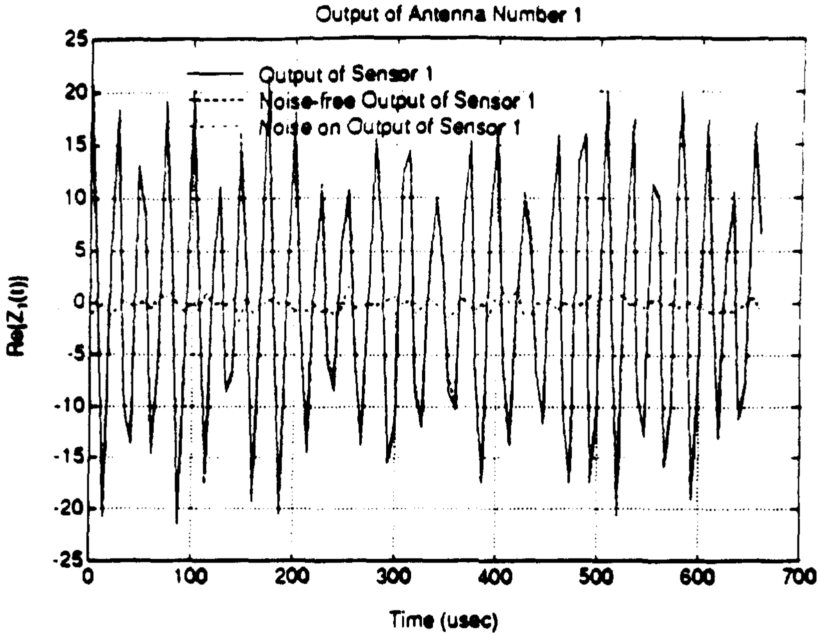

Figure 5-10: Experimental ULA Output of Sensor Number 1 - Case 2

propagation conditions and also its sensitivity to system degradations. During this period, testing will be expanded to include evaluation of the full-duplex transmit/receive SDMA system in a *controlled* RF environment. The test scenarios planned are such that the results can be readily extrapolated to real environments, allowing early preliminary performance assessment and design iteration.

5.3.2 Propagation Studies

Also during the first four months, propagation studies will be conducted in the 1850 to 1990 *MHz* band to ascertain the relevant RF properties of the environments in which the PCS SDMA system will be operating. CT-2 (FDMA platforms) will be deployed at Stevedoring Services of America (Pier 18, Port of Seattle) and at the Sheraton Seattle Hotel and Towers and technical and market surveys will be conducted.

5.3.3 Full-scale SDMA Prototype Development

Full-scale SDMA prototype development will be undertaken from August 1992 to April 1993. Using the results of the preliminary tests, an advanced engineering prototype SDMA system will be designed, constructed, and tested. The SDMA system will be integrated into a CT-2 Plus base station and after basic validation, three such base

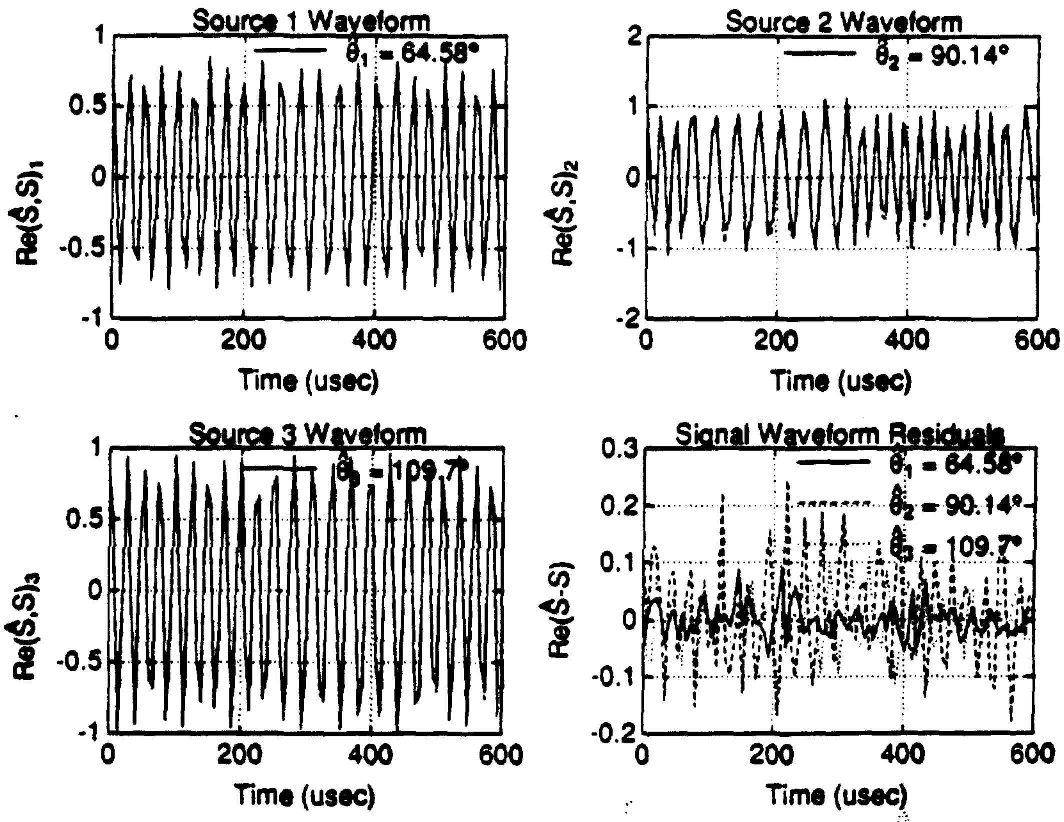

Figure 5-11: Experimental Signal Copy Results – Case 3

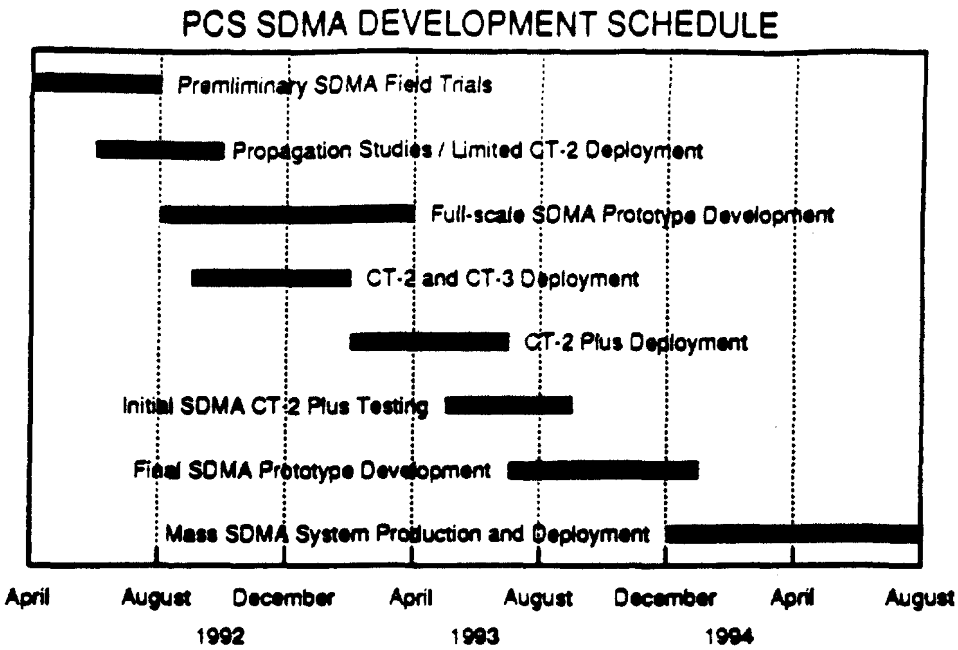

Figure 5-12: Two-Year PCS SDMA Development Plan

stations will be constructed, tested, and integrated into a small prototype network. Once complete, the hardware will be ready for installation and initial *in situ* testing.

5.3.4 CT-2 (FDMA) and CT-3 (TDMA) Platform Deployment

Deployment of the CT-2 platforms at Stevedoring Services of America and the Sheraton Seattle Hotel and Towers will be expanded from September 1992 to January 1993. A CT-2 platform will be deployed at View Ridge Elementary School (Seattle public schools) and in the adjacent residential corridor. Also, a CT-3 platform will be deployed at the Sheraton Seattle Hotel and Towers. Technical and market surveys will be conducted for each platform.

5.3.5 CT-2 Plus Platform Deployment

CT-2 Plus system deployment will begin in February 1993 at existing sites. In addition, sites in Los Angeles and Long Beach will be considered as well. Technical and market surveys will be conducted.

5.3.6 Main SDMA System Tests

Full-scale testing of the PCS SDMA system will begin in May 1993 with 200-users on a CT-2 Plus platform. System performance will be analyzed and problems solved as they are encountered. These tests will provide valuable insight into the system requirements for the final prototype design prior to mass production and system installation. Initial testing should be complete around September 1993. Apart from performance testing, extensive evaluation to verify the SDMA equipment's ability to withstand environmental conditions including temperature, humidity, shock, corrosion , *etc.*, will be carried out. Also, in parallel, reliability, maintainability and safety features will be evaluated.

5.3.7 Final SDMA Design Freeze

Final PCS SDMA prototype design improvements will begin in July 1993 and will be completed over the next six months. Based on the earlier test results and evaluations, the SDMA prototype will be re-designed and re-engineered to fully meet system requirements. Here, factors such as low cost, manufacturability, reliability, ease of installation, *etc.*, will be incorporated. The final SDMA prototype will be evaluated for one month during December 1993.

5.3.8 Mass Production and Deployment

Design release for production of PCS SDMA systems is expected by December 1993. The first production units are expected to be available in the first quarter of 1994 and will be installed and brought on-line soon thereafter.

6. SDMA Economics

SDMA offers significant performance and cost benefits in PCS applications. As described in detail in Section 3, its basic advantage is that provides significant improvements in spectral efficiency *in addition to those provided by existing and proposed technologies.* It can operate in conjunction with current modulation schemes including FDMA, TDMA, and CDMA, and is compatible with the cellular/microcellular concept for spectrum reuse. It provides capacity and quality benefits over and above the those offered by such schemes. The relationship of SDMA to such modulation schemes is analogous to that of the cellular concept to FDMA and TDMA techniques. Communication capacity (*i.e.*, spectral efficiency) is increased by exploiting the dimension of space, with SDMA doing so in an intelligent manner. In this sense, SDMA is a natural extension of the cellular concept, making cells dynamic through smart antennas and appropriate signal processing technology.

In this section, approximate costs of implementing SDMA are given, and a cost-benefit analysis is performed. It is assumed for simplicity that SDMA is deployed in a CT-2 or

CT-2 Plus system where FDMA (FSK) modulation is used. As emphasized previously, SDMA is modulation independent in its applicability and is directly applicable to CT-3 (TDMA) digital systems.

6.1 Cost-Benefit Analysis

In the subsequent analysis, costs related to handsets (portable units) and controllers required for CT-2 Plus or CT-3 system operation are not considered since these costs are not affected by SDMA implementation. Implementation of the SDMA system is essentially done on a site-by-site basis, and other than allowing more portable units to simultaneously access the system from a given base station, has no effect on system infrastructure costs. Furthermore, since the SDMA system is modulation independent, it can be employed with current and future handsets without modification thereto. The following relative base station costs are assumed.

Base Station Type	Relative Cost
CT-2 (FDMA) / CT-2 Plus	$1.0X$
CT-3 (TDMA)	$1.5X$

The estimated cost of SDMA base station upgrade hardware/software is given below.

Item	Relative Cost
Antenna Related Hardware (per antenna)	$0.001X$
RF Frontend (per antenna)	$0.1X$
DSP Processor System	$0.08X$

Thus, the total SDMA base station cost for a system with M antennas per base stations is given by:

$$\text{Cost per base station} = X(1.08 + 0.11M)$$

6.2 Relative System Cost Exploiting Capacity Gain

As explained earlier, a major advantage of SDMA is the potential for increasing system capacity. The increase in capacity due to SDMA is theoretically $M-1$, though system robustness considerations dictate a more modest figure somewhere between $M/2$ and $2M/3$. To compare the base station costs with and without the added capacity SDMA provides, the number of users can be assumed to be constant and the increase in capacity *traded* for reduced number of cells. This would be valuable in a suburban market, for example, in which though base stations might not be operating at capacity, the objective would be to minimize the number of base stations required. In the comparison to follow, infrastructure costs related to the communication required between multiple base stations is ignored.

Using the more conservative capacity increase figure of $M/2$, the relative cost of an CT-2 or CT-2 Plus SDMA base station compared to the $M/2$ base stations it replaces is given by:

$$\text{Relative Cost} = X(1.08 + 0.11M)/(M/2 \times X) = 2(1.08 + 0.11M)/M.$$

For a modest improvement of a factor of three, six antennas would be suggested and the relative cost would be approximately 0.6, *i.e.*, the CT-2 SDMA system would cost 60% of the CT-2 system without SDMA. This cost advantage can also be exploited when the system load exceeds capacity, and SDMA can be used to increase capacity without decreasing cell size as discussed in the next section.

6.3 Relative System Cost for Capacity Limited Operation

In many urban environments, system capacity is expected to be a key issue. Therein, SDMA can be used to cost effectively handle the increased capacity required. In this section, relative system costs are estimated under the assumption of *capacity limited operation*, *i.e.*, that all available channels are utilized. Assuming that there are 1500 customers in a designated area to be serviced, the following total costs can be estimated.

6.3.1 CT-2 / CT-2 Plus without SDMA

Assuming that a CT-2 base station can service 30 users, the cost of servicing 1500 users will be $50X$ since 50 base stations are required. Here it is assumed that the density of users is such that cells are not overloaded.

6.3.2 CT-2 with SDMA

If SDMA is used to increase capacity, with ten antennas per base station ($M = 10$), the cost of one SDMA base station is $2.18X$. The cost of base stations to serve 1500 mobiles (150 mobiles per base station) will be $21.8X$. Here, the conservative efficiency factor of $M/2$ has been used.

6.3.3 CT-3 without SDMA

Assuming that digital systems can provide a capacity improvement of a factor of 3, then cost of 16.33 CT-3 base stations (each 1.5 times the cost of a CT-2 base station) to serve 1500 mobiles will be $25X$.

6.3.4 CT-3 with SDMA

The increased capacity offered by SDMA will reduce number of base stations further to 3.3 while increasing each base station cost slightly. The total estimated cost of base stations will be $8.9X$ (*cf.* . $3.3 \times (1.5X + 1.18X)$).

These are summarized below.

System Type	Relative Cost
CT-2 / CT-2 Plus w/o SDMA	$50.0X$
CT-2 w/ SDMA	$21.8X$
CT-3 w/o SDMA	$45.0X$
CT-3 w/ SDMA	$8.9X$

Therefore, there are substantial gains in total system cost to be realized by using SDMA. The decrease in cost is better than a factor of 2 if SDMA is deployed with CT-2 type systems. The cost reduction when using SDMA with CT-3 digital systems is a factor of 5 relative to the standard CT-3 system. It should be noted that if the costs of handsets are factored in, assuming a CT-2 or CT-2 Plus handset costs $0.005X$ and CT-3 handsets cost three times that amount, CT-2 with SDMA offers the lowest overall cost in a capacity limited environment.

6.4 Performance Benefits

While SDMA has overall costs benefits, it also has certain performance benefits that have been described in detail previously. While some advantages can be traded to reduce costs, other performance benefits add value through quality. While it is not generally possible to put a value on such performance improvements, its effect on overall satisfaction is likely to be considerable.

APPENDIX B

SPATIAL COMMUNICATIONS, INC.
CORPORATE RESUME

SPATIAL COMMUNICATIONS, INC.
CORPORATE RESUME

J. Daniel Bariault

J. Daniel Bariault is a Director and President/CEO of Spatial Communications, J.V., Inc. and Spatial Communications, Inc. Mr. Bariault is an attorney with extensive experience in Business Development. He also has broad telecommunications knowledge.

Dr. Richard Roy

Dr. Richard Roy is a director of Spatial Communications, J.V., Inc. and Spatial Communications, Inc. and Chief Scientist of Spatial Communications, Inc. He is the lead inventor of SDMA technology. Dr. Roy has been associated with Stanford University since 1972 and was granted a Ph.D. from that school. His fields of research have focused on multidimensional signal parameter estimation, signal processing theory, and adaptive algorithms. He is widely published internationally, has been invited to speak at conferences around the world, and has been granted two patents in connection with the development of SDMA.

Martin Cooper

Martin Cooper is Chairman of the Boards of Directors of Spatial Communications, J.V., Inc. and Spatial Communications, Inc. He is widely recognized as a pioneer in the personal communications industry and as an innovator in the management of research and development. He was responsible for introduction in 1973, of the first portable cellular radiotelephone, and is regarded as the father of cellular telephony. He also led the creation of the first trunked mobile radio systems and the first high capacity paging systems. He is an IEEE Centennial Medal awardee and is a Fellow of the IEEE and the Radio Club of America for his contributions to radiotelephony.

Matthew E. Howe

Matthew E. Howe is a Director and Vice-President of Spatial Communications, J.V., Inc. and Spatial Communications, Inc. Mr. Howe has extensive experience in cellular radio and telecommunications and was formerly the Management Information Services Director for McCaw Cellular. He is also a principal and co-founder of Cellular Management Associates, Inc., a highly respected cellular consulting firm.

Dr. A. Paulraj

Dr. A. Paulraj acts in the capacity of Principal Engineer of Spatial Communications, Inc. He is co-inventor, with Dr. Roy and Dr. Thomas Kailath of SDMA. He was awarded his Ph.D. from the Indian Institute of Technology and has served as a Visiting Scientist at Stanford University. He has done research in the areas of advanced communications/radar/sonar signal processing, adaptive antennas, high speed networks, and massively parallel computers. He has supervised the development of nationwide HF digital communication system and a very large state of the art sonar system for which, along with his other scientific achievements, he was awarded two medals by the president of India. He has published over 60 journals and conference research papers, has lectured widely in the fields of signal processing and computing, and is a Fellow of the IEEE.

Dr. Thomas Kailath

Dr. Thomas Kailath, SCI's Scientific Advisor, is a Professor of Electrical Engineering at Stanford University in Palo Alto, California. Dr. Kailath is a member of the National Academy of Engineering, a life Fellow of Churchill College in Cambridge, England. A Fellow of the IEEE, and a Fellow of the institute of mathematical statistics. Dr. Kailath has served on various advisory boards and panels for many academic, government, and industrial organizations, and has published over 100 technical papers in refereed journals.

Gail Costikyan

Gail Costikyan is a Telecommunications Advisor for Spatial Communications, Inc. Ms. Costikyan has extensive telecommunications experience and was formerly the Director of Operations for Cincinnati Bell Information Services. She is also a principal and co-founder of Cellular Management Associates, Inc.

David Horn

David Horn is a Telecommunications Advisor for Spatial Communications, Inc. Mr. Horn has extensive telecommunications and systems development experience and was formerly Director of Product Development for Cincinnati Bell Information Services. He is also a principal of Cellular Management Associates, Inc.

APPENDIX C

DECLARATION OF
DR. RICHARD H. ROY

DECLARATION

I, Dr. Richard Roy, do hereby declare as follows:

1. I have a Ph.D. in Electrical Engineering from Stanford University.
2. I am presently Chief Scientist of Spatial Communications, Inc.
3. I am the lead developer of a proprietary advanced spectrum access management technology known as spatial division multiple access ("SDMA").
4. I have either prepared or reviewed the technical information contained in the Request of Spatial Communications, Inc. for a Pioneer's Preference in the Licensing Process for Personal Communications Services, and in the Appendix thereto entitled, "Implementing SDMA in the PCS Environment; Technical and Economic Factors".
5. The technical facts contained in the above-mentioned documents are accurate to the best of my knowledge and belief.

Under the penalties of perjury, the foregoing is true and correct.

May 4, 1992
Date

Richard Roy
Dr. Richard H. Roy